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Viewpoint

Good fortune from a broken mirror

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A huge, predicted atomic parity violation has now been observed in ytterbium, further aiding tabletop experimental searches for physics beyond the standard model that complement ongoing efforts at high-energy colliders.

Subject Areas: **Atomic and Molecular Physics, Particles and Fields, Nuclear Physics**

A Viewpoint on:

Observation of a Large Atomic Parity Violation Effect in Ytterbium

K. Tsigutkin, D. Dounas-Frazer, A. Family, J. E. Stalnaker, V. V. Yashchuk and D. Budker

Phys. Rev. Lett. **103**, 071601 (2009) – Published August 10, 2009

We know of four fundamental forces in nature: the electromagnetic, weak, strong, and gravitational interactions [1]. The interaction between electrons and nuclei in atoms is predominantly electromagnetic, but there are tiny effects from the weak force. The weak force only acts over a distance that is as short as 0.1% the diameter of a proton, and the size of its effects in an atom is many orders of magnitude less than that of the electromagnetic force. As a result, the weak interaction can only be detected with very high-precision experiments. Now, Konstantin Tsigutkin and colleagues at the University of California, Berkeley, US, report in *Physical Review Letters* an experiment on ytterbium (Yb) in which they have observed the largest weak interaction effect in atoms to date [2]. It is 100 times larger than what has been seen in cesium (Cs), the atom with which the first [3] and, so far, most accurate measurements [4] of the weak force in atoms have been performed and which has established the experimental basis for almost all of the research in this field. The finding of such a large effect in Yb encourages the ongoing search for the weak interaction in other heavy atoms and provides in itself an opportunity to use tabletop atomic physics techniques as part of sensitive searches for new physics beyond the standard model.

The Berkeley group performed laser measurements to determine how the weak force, which very slightly modifies the interactions between the electrons and the nucleus, affects the ground state of an Yb atom. Since the weak interaction effect is much smaller than the Coulomb interaction between the electrons and the positively charged nucleus, a *tour de force* in experimental efforts is required to extract it from the transition rate between the ground state and an excited state. Tsigutkin *et al.*'s experimental success is based on careful quantum mechanical interference techniques and their ability to thoroughly control systematic effects that could otherwise mimic a signal. But to fully appreciate the Berkeley group's experimental art, some background is first re-

quired.

The standard model of particle physics describes every known electromagnetic, weak, or strong process in nature in one coherent picture over the entire energy range that is currently accessible by experiment [1]. We know that matter consists of fundamental fermions: the leptons such as the electron, and the quarks, which form hadrons such as protons and neutrons. The forces between the matter particles are mediated through the exchange of "gauge" bosons. These are the massless photons γ for electromagnetism, massive Z^0 , W^+ , and W^- bosons for weak processes, and eight gluons for the strong interaction.

The weak force is special because it does not respect certain discrete symmetries. These include the parity (P) (or, the mirror symmetry), which describes the symmetry between right- and left-handed particles; charge conjugation (C), which is the exchange of particles by antiparticles, i.e., particles with the same mass but opposite charge; and the combination of these two symmetries (CP). Scientists first observed parity violation in 1957 with a crucial pioneering experiment on the β -decay of polarized ^{60}Co nuclei [5] where it was found that electrons are emitted preferentially in the direction of the nuclear spin. The standard model explains this process by assuming that the W^\pm bosons that govern the weak interaction only exist in a left-handed version.

One outgrowth of the standard model is that the electromagnetic and weak interactions are really just different manifestations of one single electroweak force. This unification led to the prediction of another neutral boson called the Z^0 , which was observed in both high-energy neutrino scattering experiments [6] and at low energies in atoms. The discovery of Z^0 removed any doubts about the general correctness of the theory [7] and became a crucial success of the standard model. The Z^0 boson exchange in atoms between electrons and nuclei

is associated with parity violation and manifests itself, for example, by different absorption of left- and right-circularly polarized light [3].

The virtual particles that carry the electroweak force can exist only for a short time Δt , given by the energy corresponding to their mass m_X and the Heisenberg uncertainty relation. This gives them a range $r_X = c\Delta t \approx \hbar/(m_X c)$, which for photons is infinite, but for weak bosons is only 1/1000 of the diameter of a proton or neutron. As a consequence, the weak effects in atoms are very small and only affect those electrons with wave functions that overlap with the nucleus, such as the ground state in Yb. Since the weak effects are so small, we can fairly accurately calculate the electronic energy levels in atoms using only parity conserving electromagnetic interactions and a purely electromagnetic Hamiltonian describing the Coulomb interaction between electrons and the nucleus, which is mediated by γ exchange. The additional small contribution from Z^0 boson exchange can be treated as a perturbation that mixes wave functions of different parity, i.e., the true energy levels in the atom correspond to mixtures of different parity electromagnetic states [8]. Now, the closer states of opposite parity are to each other in energy, the larger their mixing will be. In this respect, nature has bequeathed Yb with a favorable atomic structure in which weak effects are actually quite large [9]. In addition, in the standard model the strength of weak interactions is characterized by a quantity called the weak charge Q_W , which is determined primarily by the number of neutrons in the nucleus (the protons play only a minor role). The size of parity violation effects in atoms also scales approximately with Z^3 , which favors observing such effects in heavy atoms, like Yb[8], or heavier.

The experimental challenge in the Yb atom experiment performed by the Berkeley group is to make the tiny parity violating effect visible. For that, the authors have chosen to laser excite the “forbidden” transition $^1S_0(6s^2)$ to $^3D_1(5d6s)$ at 408-nm wavelength. Because Z^0 boson exchange mixes the 3D_1 state with the $^1P_1(6s6p)$ state, there is a tiny transition amplitude ζ for this otherwise forbidden transition. This amplitude would provide a measure of the weak interaction, but it cannot be measured directly. The trick therefore is to place the Yb atoms in a combination of static magnetic and electric fields [2, 4]. The magnetic field splits the magnetic sublevels in the excited state (the Zeeman effect). The electric field E also mixes atomic states of opposite parity (the Stark effect), which interferes with the parity mixing in the atom and yields a strong enhancement of the overall observable effect. In particular, two terms arise in the transition rate R between the ground state and individual Zeeman levels. One of them is determined by the Stark effect only and is proportional to E^2 and the second one (represented pictorially in Fig. 1) comes from the interference between the Stark effect and the weak interaction and is proportional to $\zeta \cdot E$. Hence $R \propto aE^2 + b\zeta \cdot E$, where the constants a and b depend on

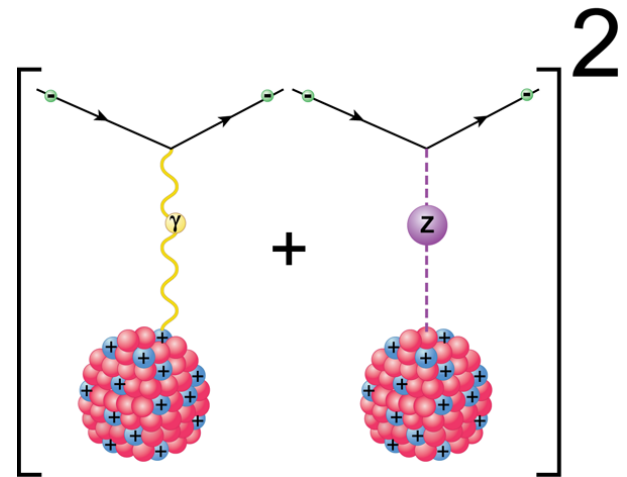


FIG. 1: Electrons in an atom interact with the nucleus through the electromagnetic force via the exchange of massless photons (γ). The weak force is mediated by Z^0 bosons. The weak effects by themselves are too small to see directly. However, it is possible to measure the effect of Z^0 boson exchange between an electron and a neutron by looking at the quantum mechanical interference between this process (right) and the electromagnetic interaction (left). The figure provides a pictorial representation of how the quantum interference between the two processes—the sum of the amplitudes squared—contributes to a measurable signal. (Illustration: Carin Cain)

the states involved in the transition and the light polarization and intensity. To separate out the second, much smaller term, the Berkeley group modulates the electric field at a frequency Ω_M . The transition rates then contain a part that depends on ζ and oscillates at Ω_M and another part that oscillates at $2\Omega_M$. With a modulation phase and frequency sensitive detection (lock-in) method they were able to produce a signal at Ω_M , from which the parity violation amplitude can be extracted, on top of a background that is some 25 times larger than the signal itself.

The measurement at Berkeley demonstrates that it is possible to observe parity violating effects in complicated atoms such as Yb. This is an exciting result, because there are seven stable isotopes of Yb. The strong dependence of the weak charge on the neutron number means it will be possible to study the effect of nuclear neutron distributions on the weak interaction in Yb[10]. The so-called anapole moments, which reflect the parity violating interaction between a single (valence) nucleon and the core of an atomic nucleus [11], can be accessed by looking at different hyperfine components in isotopes with odd neutron number. These experiments are very sensitive to small perturbations and systematic errors, but the Berkeley group shows that with time they should be able to minimize these problems.

The Ytterbium experiment can potentially go further than verifying physics within the standard model—it may permit future sensitive searches for new physics

beyond the standard model. It's not surprising that the theory may need to be extended, given that there are still many open questions, among them why there are exactly six leptons and six quarks, and which mechanisms underlie certain symmetry breakings.

Beyond Yb, there are a number of complementary experiments on their way that use isotopes of the alkali atom francium (Fr) [12] or of the alkali-like barium ion (Ba^+) [13] and radium ion (Ra^+) [14]. (The theoretically predicted enhancement factors of weak effects in these atoms compared to Cs are 2.3, 16, and 52.) The atomic structure of these two atoms is simpler and easier to calculate than that of Yb. The combination of advanced calculations and these precision experiments will allow us to determine the weak charge Q_W to much better than 1% accuracy. Together, these atomic parity violation experiments has the great potential to reveal new physics such as a new weak boson $Z^{0'}$, supersymmetric particles, leptoquarks, or smaller components making up the matter building fundamental fermions, all of which would cause a modification of the weak charge and the Weinberg angle (a free parameter in the equation that determines the strength of the weak interaction) [12–16]. Alternatively they can provide important limits on parameters in such models, which have been suggested to extend the standard model, and thereby steer theoretical model building—just as cutting edge experiments in Cs and its subsequent theoretical exploitation continue to do [16].

More than 50 years after the discovery of mirror symmetry breaking in physics, the subject remains lively and has a robust chance to provide new surprises. The large weak effects in heavy atoms, such as what the Berkeley group has demonstrated in Yb, open a new round for exploiting the broken mirror symmetry and

shine new light on the yet not-understood features of the standard model.

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About the Author

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Klaus Jungmann studied physics at the University of Heidelberg, Germany, and was later a post-doctoral researcher at IBM Almaden Research Center in San Jose, California. He is currently a full professor at the University of Groningen and director of the Kernfysisch Versneller Institute, which oversees a dedicated facility (TRIμP) for research on fundamental interactions and symmetries at low energies. His research interests lie at the interface between atomic, particle, and nuclear physics in precision experiments. This includes the determination of fundamental constants and searches for new physics with free muons and the muonium atom.